Bound on the tau neutrino magnetic moment from the Super-Kamiokande data

S.N.Gninenko[1]

CERN, CH-1211 Geneva 23, Switzerland
and
Institute for Nuclear Research, RAS , Moscow 117312, Russia

Abstract

It is shown that recent results from the Super-Kamiokande detector constrain the tau neutrino diagonal magnetic moment to $\mu_{\nu_\tau} < 1.3 \times 10^{-7}\mu_B$ for the case of $\nu_\mu \to \nu_\tau$ interpretation of the atmospheric neutrino anomaly. It is pointed out that the large magnetic moment of the tau neutrino could affect further understanding of the origin of the anomaly.

Recent results from the Super-Kamiokande (S-K) detector give evidence for neutrino oscillations [1] - [4]. One of the favourable interpretations of the atmospheric neutrino anomaly suggested by the S-K collaboration is related to the existence of $\nu_\mu \to \nu_\tau$ neutrino oscillations. This implies that tau neutrinos have non-zero masses and therefore may also have a non-zero diagonal magnetic moment (see e.g. ref. [5]). As a consequence, massive tau neutrinos could manifest themselves in terrestrial experiments through the effect of $\nu_\mu \to \nu_\tau$ neutrino oscillations, and, if the magnetic moment value is large enough, through tau neutrino electromagnetic interactions.

In ref.[6] (see also [7]), it was shown that the combined existence of $\nu_\mu \to \nu_\tau$ (and/or $\nu_e \to \nu_\tau$) oscillations and non-zero magnetic moment of the tau neutrino would increase the total rate of events in $\nu_\mu(\nu_e)$ neutrino- electron scattering experiments. It was used to constrain the mixing angles of the tau neutrino with neutrinos of another flavour. In this Letter it is shown that this effect can also be used to constrain the magnetic moment of the tau neutrino from the S-K atmospheric neutrino data.

Assuming that a muon neutrino beam has a component of tau neutrinos due to $\nu_\mu \to \nu_\tau$ oscillations, in the case of two-neutrino mixing, neutrino states evolve with time t as

$$|\nu(t) >= a(t)|\nu_\mu > +b(t)|\nu_\tau, \mu_{\nu_\tau} \neq 0 > \tag{1}$$

[1] Sergei.Gninenko@cern.ch

where $|\nu_\mu>$ and $|\nu_\tau>$ denote weak eigenstates of ν_μ and ν_τ neutrinos, and $a^2(t)$, $b^2(t)$ are the probabilities of finding ν_μ or ν_τ in the beam at a given moment t, respectively. It is assumed that $a^2(0) = 1$ at $t = 0$. The probability $b^2(t)$ depends on the parameters of $\nu_\mu - \nu_\tau$ oscillations as [8]:

$$b^2(t \simeq \frac{L}{c}) = P(\nu_\mu \to \nu_\tau) = sin^2 2\theta_{\mu\tau} sin^2 \frac{\Delta m^2 L}{4E_\nu} \tag{2}$$

or

$$P(\nu_\mu \to \nu_\tau) \approx sin^2 2\theta_{\mu\tau} sin^2 \frac{1.27\Delta m^2(eV^2)L(km)}{E_\nu(GeV)} \tag{3}$$

where $sin^2 2\theta_{\mu\tau}$ is the mixing angle, $\Delta m^2 = \left|m_3^2 - m_2^2\right|$ is the difference of the squares of the mass eigenstates in eV^2, E_ν is the neutrino energy in GeV, and L is the mean distance between the neutrino source and the detector in km. In the above formula it is also assumed that magnetic field B is weak enough not to affect the probability of oscillations $P(\nu_\mu \to \nu_\tau)$, i.e. [9]:

$$\Delta m^2/2E_\nu \gg \mu_{\nu_\tau} B \tag{4}$$

Then if the magnetic moment of the ν_τ exists, it will contribute to a non-coherent part of the $\nu_\tau e^-$ scattering cross section via the reaction that changes the helicity of the tau neutrino (hence right-handed neutrino states should exist). This might result in a contribution to the observed deviations from unity of the flavour ratio of the atmospheric neutrino flux, $R \equiv \big((N_{\nu_\mu} + N_{\overline{\nu}_\mu})/(N_{\nu_e} + N_{\overline{\nu}_e})\big)_{data} / \big((N_{\nu_\mu} + N_{\overline{\nu}_\mu})/(N_{\nu_e} + N_{\overline{\nu}_e})\big)_{MC}$, in the S-K detector for both data and Monte Carlo (MC) simulation. Here, $N_{\nu_\mu,\overline{\nu}_\mu}$ and $N_{\nu_e,\overline{\nu}_e}$ are the number of muon -like (μ-like) and electron-like (e-like) fully-contained events in the S-K detector [1].

Indeed, since the electromagnetic cross section is orders of magnitude larger than the weak cross section, even a small fraction of tau neutrinos with non-zero magnetic moment in the atmospheric neutrino flux could lead to an observable excess of isolated electrons in atmospheric neutrino interactions in the S-K detector whose signature is identical to that of e-like events. Note that the magnetic moments of muon or electron neutrino are experimentally proved to be too small to give a noticeable contribution to the neutrino interaction rate. The production rate of isolated electrons via $\nu_\tau e^-$ scattering in the detector depends on the probability $P(\nu_\mu \to \nu_\tau)$ of finding ν_τ neutrinos in the atmospheric neutrino flux. This probability can be calculated from the neutrino survival and transition probabilities using Eq.(2).

The neutrino-electron scattering process via magnetic moment has a cross section [10]:

$$\frac{d\sigma_\mu}{dE_e} = \frac{\pi\alpha^2}{m_e^2}\frac{\mu_\nu^2}{\mu_B^2}\Big(\frac{1}{E_e} - \frac{1}{E_\nu}\Big) \tag{5}$$

where E_e is the electron energy, μ_ν is the neutrino magnetic moment and $\mu_B = e/2m_e$ is Bohr magneton. For the case of constant E_ν the integral cross section is

$$\begin{aligned} \sigma_\mu &= \frac{\pi\alpha^2}{m_e^2}\frac{\mu_\nu^2}{\mu_B^2}\Big[ln\Big(\frac{E_e^{max}}{E_e^{min}}\Big) - \frac{(E_e^{max} - E_e^{min})}{E_\nu}\Big] \\ &= 2.7\times 10^{-39}\Big(\frac{\mu_\nu}{10^{-7}\mu_B}\Big)^2\Big[ln\Big(\frac{E_e^{max}}{E_e^{min}}\Big) - \frac{(E_e^{max} - E_e^{min})}{E_\nu}\Big]\ cm^2 \end{aligned} \tag{6}$$

where E_e^{max}, E_e^{min} are the high and low electron energy cuts, respectively. Note that the integral cross- section σ_μ depends very weakly on the neutrino energy. It rises only logarithmically with the neutrino energy, while the total neutrino cross section rises linearly with E_ν. Thus, it is advantageous to search for a tau neutrino magnetic moment using the low energy (sub-GeV, $E_{visible} < 1.33$ GeV) S-K data [1].

Approximately, all atmospheric neutrino giving rise to the fully contained μ-like events in the S-K detector have energy above 400 MeV, see e.g. Ref. [11] (MC studies showed the mean neutrino energy for CC interactions to be about 800 MeV for μ-like events [1]). Thus, for the lowest electron energies analysed in the S-K, from $E_e^{min} = 100$ MeV to $E_e^{max} = 200$ MeV (first bin of the histogram in Fig.4(a) corresponding to e-like events, ref. [1]), the cross section of $\nu_\tau - e$ scattering due to non-zero magnetic moment is

$$\sigma_\mu = 1.2\times 10^{-39}(\mu_\nu/10^{-7}\mu_B)^2\ cm^2 \tag{7}$$

Here, we assume the tau neutrino energy $E_\nu = 400$ MeV, thus the integral cross section is underestimated.

The total number ΔN_e of e-like events from $\nu_\tau - e$ scattering in the first energy of Fig.4(a) in [1] can be written in the form

$$\Delta N_e = \int k_0\cdot f_\nu\cdot\sigma_\mu\cdot\varepsilon\cdot d\Omega\cdot dE_\nu = k_1 N_{\nu_\tau}\sigma_\mu \tag{8}$$

where k_0 is a factor related to the ν-target mass, f_ν is tau neutrino flux, the cross section σ_μ is constant, ε is detection efficiency which is practically independent of energy for $E_e > 100$ MeV [1], k_1 is a factor corresponding to the convolution of detector acceptance, detection efficiency and ν-target mass

and N_{ν_τ} is the total number of tau-neutrinos crossing fiducial volume of the S-K detector.

The number of tau-neutrinos is estimated using the number of the *initially* produced muon atmospheric neutrino:

$$N_{\nu_\tau} = (N_{\nu_\mu} + N_{\overline{\nu}_\mu})\overline{P}(\nu_\mu \to \nu_\tau) \tag{9}$$

The observation of the small value of $R = 0.61 \pm 0.03(stat.) \pm 0.05(syst.)$ [1] and zenith angle dependent deficit of μ-like events suggests, that in the case of two -neutrino oscillation scenario of $\nu_\mu \to \nu_\tau$ more than 30% (90%$C.L.$) of the initially produced muon neutrinos arrive at the S-K detector as tau neutrinos [2, 3]. We assume that the average probability of oscillations $\overline{P}(\nu_\mu \to \nu_\tau) = 0.3$.

Muon-neutrino quasi-elastic events detected in the S-K detector were used to estimate the expected total number of muon neutrino. Similarly to Eq.(8) one can write

$$\begin{aligned} N_\mu^{q.e.} &= k_2(N_{\nu_\mu}\sigma^{\nu}_{q.e.} + N_{\overline{\nu}_\mu}\sigma^{\overline{\nu}}_{q.e.})\Big(1 - \overline{P}(\nu_\mu \to \nu_\tau)\Big) \\ &= k_2(N_{\nu_\mu} + N_{\overline{\nu}_\mu})\Big(1 - \overline{P}(\nu_\mu \to \nu_\tau)\Big)\overline{\sigma}_{q.e.} \end{aligned} \tag{10}$$

where k_2 has the same meaning as k_1 in Eq.(8), and $\sigma^{\nu}_{q.e.}$,$\sigma^{\overline{\nu}}_{q.e.}$ are the cross-sections of quasi-elastic scattering of muon neutrino on (bounded) neutrons and anti-muon neutrino on protons in the H_20-target, respectively, which were taken to be constant and to be equal to its maximal values of $\sigma^{\nu}_{q.e.} = 1.0 \times 10^{-38}$ cm^2 and $\sigma^{\overline{\nu}}_{q.e.} = 0.4 \times 10^{-38}$ cm^2 in the energy region E_ν <1.33 GeV, see e.g. [11]. The average cross section $\overline{\sigma}_{q.e.} = (\sigma^{\nu}_{q.e.} + \sigma^{\overline{\nu}}_{q.e.})/2$, since according to MC simulation used in the experiment the ratio $N_{\nu_\mu}/N_{\overline{\nu}_\mu} = 1$ within a few percent for the neutrino energy range considered [12]. Thus, the total muon neutrino flux is underestimated. The number of detected quasi-elastic muon-neutrino events can be extracted from the number of μ-like events in Table 1 of ref.[1]. Under the $\nu_\mu \to \nu_\tau$ oscillation hypothesis used the fractions of $\nu_e CC$, $\nu_\mu CC$ and NC events in a detected sample of μ-like events calculated for $\overline{P}(\nu_\mu \to \nu_\tau) = 0.3$ should be 0.7%, 94% and 5.3%, respectively, instead of 0.5%, 95.8% and 3.7% given in Table 1 of ref.[1]. Thus, $N_\mu^{q.e.} = 900 \times .94 \times 916.9/1166.5 = 665$ events. We also assume that the final state signature in water Cherenkov detectors are practically the same for quasi-elastic ν_e and $\nu_\tau - e$ elastic scattering processes, so detection efficiencies for these processes are the same. The efficiencies for identifying quasi-elastic ν_e and ν_μ events were 93% and 95%, respectively [1]. Finally, since detection efficiences for fully-contained e-like (P_e >100 MeV/c) and μ-like (P_μ > 200 MeV/c) events are practically energy independent we neglect this small difference in efficiencies and assume that $k_1 = k_2$.

Using the above value for $N_\mu^{q.e.}$, Eqs.(7-10) and $\mu_{\nu_\tau} = 5.4 \times 10^{-7}\mu_B$, which corresponds to the BEBC experiment upper limit on diagonal tau neutrino magnetic moment [13], it is found that in the first bin of histogram in Fig.4(a) [1] the S-K experiment should detect:

$$\Delta N_e^1 = N_\mu^{q.e.} \cdot \frac{\overline{P}(\nu_\mu \to \nu_\tau)}{1-\overline{P}(\nu_\mu \to \nu_\tau)} \cdot \frac{\sigma_\mu}{\overline{\sigma}_{q.e.}} \simeq 1420 \; events \tag{11}$$

This number is much greater than the number of observed events, $N_{e,data}^1 = 160$ events, or the number of events predicted by MC simulation, $N_{e,MC}^1 = 125$ events in this energy bin. [2]

The bound for the tau neutrino magnetic moment can be calculated by using the following relation :

$$N_\mu^{q.e.} \cdot \frac{\overline{P}(\nu_\mu \to \nu_\tau)}{1-\overline{P}(\nu_\mu \to \nu_\tau)} \cdot \frac{\sigma_\mu}{\overline{\sigma}_{q.e.}} < (\Delta N_e^1)^{90} \tag{12}$$

where $(\Delta N_e^1)^{90} = (N_{e,data}^1 - N_{e,MC}^1)^{90}$ ($\simeq 80$ events) is the 90% $C.L.$ upper limit for the expected number of e-like events from $\nu_\tau - e$ scattering in the first energy bin of Fig.4(a) (ref.[1]), calculated taken into account the systematic uncertainty in the absolute normalisation of the MC events of 25% [1] by added the errors in quadrature to the statistical error.

This results in a conservative bound

$$\mu_{\nu_\tau} < 1.3 \times 10^{-7}\mu_B \tag{13}$$

The bound is a factor 4 better than the previously published bound obtained by the BEBC experiment [13] and is obtained on the assumption that $\nu_\mu \to \nu_\tau$ oscillations are the origin of the anomaly in atmospheric neutrino data observed by the S-K experiment. It can be improved by a more detailed analysis of the S-K data. Note that Eq.(4) and limit of Eq.(13) are consistent for the region of $\Delta m^2 \sim (10^{-3} - 10^{-2})$ eV^2 suggested by the S-K analysis [4], $E_\nu \simeq O(1$ GeV) and for B equal to the average magnetic field of the earth (B$\lesssim$1 Gauss).

In the S-K detector, the oscillation scenario was checked by using π^0 events [1]. For $\nu_\mu \to \nu_\tau$ oscillations the number of neutral -current (NC) events should be unchanged by neutrino oscillations. For $\nu_\mu \to \nu_\tau$ oscillations the number of $\nu_e CC$ events (e-like events) should also be unchanged by neutrino oscillations. Therefore, the (π^0/e) ratio of the data should agree with the same ratio of the Monte Carlo without oscillations for $\nu_\mu \to \nu_\tau$ case [4]. It was obtained

[2] These numbers were read off Fig.4(a) of ref.[1]

$(\pi^0/e)_{data}/(\pi^0/e)_{MC} = 0.93 \pm 0.07(stat) \pm 0.19(syst)$ (preliminary). The result is consistent with the $\nu_\mu \rightarrow \nu_\tau$ interpretation of the S-K data, however it cannot exclude $\nu_\mu \rightarrow \nu_s$ oscillation hypothesis completely.

In a recent publication [14], it was pointed out that a large diagonal and/or transition magnetic moment of neutrino can contribute to the neutral current effects (by a single π^0 production) used to distinguish the mechanisms of muon neutrino oscillation to tau neutrino or to a sterile neutrino. The effect discussed in the present Letter, as well as the effect discussed in ref. [14], definitely can affect the interpretation of atmospheric neutrino data.

Finally note that helicity flipped states of neutrinos with the large magnetic moment would be trapped in the SN1987a core, so there is no limit on the neutrino magnetic moment form SN1987a [15]. Others astrophysical constraints on μ_{ν_τ} are also model dependent and have considerable theoretical and experimental uncertainties.

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